

# Application of Autonomous Smart Inverter Volt-VAR Function for Voltage Reduction Energy Savings and Power Quality in Electric Distribution Systems

### **Preprint**

Fei Ding, Adarsh Nagarajan, Murali Baggu, and Sudipta Chakraborty

National Renewable Energy Laboratory

Andu Nguyen, Sarah Walinga, Michael McCarty, and Frances Bell *SolarCity* 

To be presented at the Eighth Conference on Innovative Smart Grid Technologies (ISGT 2017) Washington, D.C. April 23–26, 2017

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Conference Paper NREL/CP-5D00-67600 April 2017

Contract No. DE-AC36-08GO28308

### NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http://www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI <a href="http://www.osti.gov">http://www.osti.gov</a>

Phone: 865.576.8401 Fax: 865.576.5728 Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce National Technical Information Service 5301 Shawnee Road Alexandria, VA 22312 NTIS http://www.ntis.gov

Phone: 800.553.6847 or 703.605.6000

Fax: 703.605.6900 Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

## Application of Autonomous Smart Inverter Volt-VAR Function for Voltage Reduction Energy Savings and Power Quality in Electric Distribution Systems

Fei Ding, <sup>1</sup> Member, IEEE, Andu Nguyen, <sup>2</sup> Member, IEEE, Sarah Walinga, <sup>2</sup> Member, IEEE, Adarsh Nagarajan, <sup>1</sup> Member, IEEE, Murali Baggu, <sup>1</sup> Senior Member, IEEE, Sudipta Chakraborty, <sup>1</sup> Senior Member, IEEE, Michael McCarty, <sup>2</sup> Member, IEEE, and Frances Bell, <sup>2</sup> Member, IEEE

<sup>1</sup> National Renewable Energy Laboratory, Golden, CO 80401; <sup>2</sup> SolarCity, San Francisco, CA 94107

Abstract — This paper evaluated the impact of smart inverter Volt-VAR function on voltage reduction energy saving and power quality in electric power distribution systems. A methodology to implement the voltage reduction optimization was developed by controlling the substation LTC and capacitor banks, and having smart inverters participate through their autonomous Volt-VAR control. In addition, a power quality scoring methodology was proposed and utilized to quantify the effect on power distribution system power quality. All of these methodologies were applied to a utility distribution system model to evaluate the voltage reduction energy saving and power quality under various PV penetrations and smart inverter densities.

Index Terms — photovoltaic, smart inverter, Volt-VAR, CVR, voltage reduction, energy saving, power quality.

### I. INTRODUCTION

DISTRIBUTED solar photovoltaics (PV) with smart inverters not only provide active power, but can also supply or absorb reactive power, which provides the capability of controlling local voltage and power factor. This is achieved through various setting modes including Volt-VAR control that dynamically controls the reactive power output based on the local voltage.

Conservation voltage reduction (CVR) is a methodology of lowering voltage on a circuit in order to reduce energy consumption [1], [2]. Traditional CVR employs local device settings to control load tap changers (LTCs), voltage regulators, and shunt capacitors. To achieve more energy savings through voltage reduction, a centrally controlled voltage optimization (VO) scheme can be used. Distributed PV with smart inverters' ability to regulate local voltage can be used to compliment a utility CVR VO scheme. Previous research has shown that regulating local voltage at the secondary level could benefit voltage reduction [3]. This paper summarizes a report completed by National Renewable Energy Laboratory (NREL) and SolarCity [4] in which a detailed methodology is developed to co-optimize the operations of substation LTC, capacitor, and distributed smart inverters for voltage reduction. The methodology and energy saving results are consolidated in this paper.

Voltage reduction applications impact the power quality of a system. Power quality, including voltage range, control device operations, energy losses, etc., is of great significance to evaluate the "health" of a distribution system. Some existing studies have shown that distributed PV with smart inverter can help improve power quality [5], [6]. The individual components that make up power quality are easy to measure; however, a comprehensive method to incorporate all of these values into a single score does not yet exist in the literature. Thus, NREL and SolarCity developed a methodology to quantify the power quality using the single number called the power quality score (PQS). The PQS results are also consolidated and presented in this paper.

Both the voltage reduction optimization and PQS methodologies were applied to a real-world utility distribution system model. The model started from the secondary of the substation transformer and extended to the end of the distribution service transformer secondary lines. Annual quasi-static time series (QSTS) simulations were run with varying levels of PV penetrations and smart inverter densities. Voltage reduction energy savings and PQS for different scenarios were calculated to assess the impact of smart inverter Volt-VAR control.

### II. VOLTAGE REDUCTION OPTIMIZATION METHODOLOGY

The impact of distributed energy resources (DERs) has not been considered in most voltage reduction studies because DERs were not allowed to participate in voltage regulation until 2014, when an amendment was made to the DER interconnection standard (IEEE 1547a [7]). This amendment allows inverter-based generation to participate in distribution feeder voltage regulation. By adding distributed PV with smart inverters at various locations on a distribution circuit, there is an opportunity to control the secondary voltages and, in aggregate, the primary voltages.

### A. Measuring the Voltage Reduction Effect

In this paper, CVR VO was used to reduce energy consumption. The voltage reduction effect was evaluated using energy savings, which was the total energy consumption reduction and was defined as:

$$VRsaving = \frac{Energy_{VR} - BaseEnergy_{noVR}}{BaseEnergy_{noVR}} \cdot 100\% \qquad (1)$$
 Where,  $BaseEnergy_{noVR}$  and  $Energy_{VR}$  were the total annual

Where,  $BaseEnergy_{noVR}$  and  $Energy_{VR}$  were the total annual energy consumption from the customer loads before and after implementing voltage reduction scheme.

CVR factor of a load is defined as the percentage change in energy consumption per percent change in the load's voltage. Real power CVR factor typically ranges from 0.5-0.9 and reactive power CVR factor typically ranged from 3-5 in [8]

and [9]. In this paper, real and reactive CVR factors were set to 0.8 and 4.0 for the simulated load models.

### B. Voltage Reduction Optimization Algorithm

Fig. 1 shows the CVR VO algorithm used for the study. The algorithm coordinated the control of substation LTC, shunt capacitors and smart inverters in order to achieve the maximum voltage reduction. The voltage reduction scheme was divided into three main operations: 1) Switching capacitor banks to flatten the voltage; 2) Operating the substation LTC to lower the flattened voltage; 3) Enabling smart inverters with autonomous Volt-VAR control.

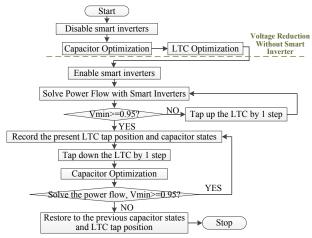


Fig. 1. Flowchart of the CVR VO algorithm with smart inverters.

### (1) Capacitor Optimization

The objective of capacitor optimization was to achieve the flattest voltage profile, i.e. the smallest difference between the maximum and minimum voltages in the distribution system. It was implemented using an exhaustive search of all possible capacitor states and the state that led to the smallest voltage difference was considered as the optimal solution.

### (2) LTC Optimization

LTC tap position was optimized by heuristically selecting the lowest possible position without causing any voltage violation of less than 0.95 pu across all the nodes of the distribution system.

### (3) Autonomous Smart Inverter Volt-VAR Control

The reactive power output of the smart inverter was based on its local voltage and a pre-defined Volt-VAR Curve (VVC). Fig. 2 shows a typical VVC, which is determined by three parameters including the voltage center of the curve (vvcCenter), the voltage width of the curve (vvcWidth), and the dead band (vvcDeadbandWidth).

### (4) Coordinated Voltage Reduction Control

As shown in Fig. 1, at the beginning of the simulation all smart inverters were disabled and all PV systems were at unity power factor to avoid affecting the traditional voltage reduction scheme. The capacitor optimization was implemented to flatten the voltage profile. Then, the LTC optimization was implemented to find the lowest tap position to lower the voltage profile without violating ANSI limit [10].

Next, smart inverters were enabled using a VVC, which had been determined in advance by selecting the best curve from several candidates to achieve the largest energy savings. The new voltage profile with the participation of smart inverters was checked. If the lowest voltage was below 0.95 pu, the LTC position was increased step by step until the minimum voltage exceeded or was equal to 0.95 pu.

Finally, iterative operations of lowering the LTC position and optimizing the capacitors were performed to allow additional voltage reduction when possible. The iterative process stopped when voltage violation occurred and a lower LTC position was not possible.

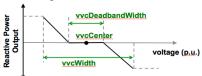


Fig. 2. A typical Volt-VAR curve [11].

### III. POWER QUALITY SCORING METHODOLOGY

The power quality scoring methodology described below was used to measure the power quality with various PV penetrations and smart inverter densities.

### A. Power Quality Metrics

Six different metrics were developed based on the components that impact power quality. All the voltage and power values used in six metrics were root-mean-square (RMS) values. Since load demand and PV generation on distribution feeders were time-varying, QSTS analysis was used to measure the PQS. The details about each metric are discussed below.

## (1) System Average Voltage Magnitude Violation Index (SAVMVI)

Let  $V_{min}$  and  $V_{max}$  be the minimum and maximum allowable values for steady-state voltage magnitudes. The voltage magnitude violation at a location i and a simulation time point t, denoted as  $VIO_{Vmag}^{i}(t)$ , was defined as:

time point 
$$t$$
, denoted as  $VIO_{Vmag}^{i}(t)$ , was defined as:
$$VIO_{Vmag}^{i}(t) = \begin{cases} V_{max} - V_{mag}, & \text{if } V_{mag} > V_{max} \\ 0, & \text{if } V_{min} \leq V_{mag} \leq V_{max} \\ V_{mag} - V_{min}, & \text{if } V_{mag} < V_{min} \end{cases}$$
(2)

If a bus has two or three phases, the average value of all phase voltage magnitude violations was used. SAVMVI averages the voltage magnitude violations for all buses at all time steps.

$$SAVMVI = \frac{1}{N} \cdot \left( \frac{1}{T} \sum_{i=1}^{N} \sum_{t=1}^{T} VIO_{Vmag}^{i}(t) \right)$$
 (3)

Where, T is the number of time steps; N is the number of buses.

The value obtained from (3) was the raw value of the power quality metric SAVMVI, which was converted to a score for calculating the final PQS. As a result, the upper and lower limits of the raw values were defined for normalization purpose.

If SAVMVI was zero, there were no voltage magnitude violations on the distribution system for the entire simulated

period. A higher SAVMVI meant more voltage violations observed. ANSI C84.1-2011 [10] specifies the maximum and minimum voltage for abnormal conditions (Range B) as 127 V (1.0583 pu) and 110V (0.9167 pu) respectively. These values were used to define the maximum possible violation as below.

$$VIO_{V_{mag}}^{max} = ma x\{1.0583 - V_{max}, V_{min} - 0.9167\} = 0.0333$$
 (4)

Therefore, the maximum of SAVMVI was:

$$max(SAVMVI) = 0.0333 \tag{5}$$

### (2) System Average Voltage Fluctuation Index (SAVFI)

Let  $V_{mag}^t$  be the voltage magnitude in per unit at a time step t. Then, voltage fluctuation was defined as the individual difference in voltage magnitude of two time steps:

$$\Delta V(t) = \left| V_{mag}^{t+1} - V_{mag}^t \right| \tag{6}$$

SAVFI was defined as the average of voltage fluctuations:

$$SAVFI = \frac{1}{N} \cdot \left( \frac{1}{T} \sum_{i=1}^{N} \sum_{t=1}^{T} \Delta V_i(t) \right)$$
 (7)

Where,  $\Delta V_i(t)$  was the voltage fluctuation at a time step t for the observed location i, as described in (6).

If SAVFI was zero, the node voltage was constant for the entire simulated period. A higher SAVFI meant larger voltage fluctuations. IEEE Std 1453-2015 [12] lists the thresholds for rapid voltage changes, inherited from IEC 61000-3-7. A 3% limit is recommended for voltage fluctuations occurring 2 to 10 times per hour on medium-voltage systems. While this RVC recommendation does not relate to these types of slow voltage fluctuations, this value was used as the maximum value for  $\Delta V_i(t)$ , which led to the maximum value of 0.03 for SAVFI.

### (3) System Average Voltage Unbalance Index (SAVUI)

SAVUI was defined as the average value of voltage unbalance based on three-phase buses:

$$SAVUI = \frac{1}{N} \cdot \left(\frac{1}{T} \sum_{i=1}^{N} \sum_{t=1}^{T} V_{imb}(t)\right)$$
 (8)

Where,  $V_{imb}(t)$  was the voltage unbalance at a time step t for the observed three-phase location i.

If SAVUI was zero, three-phase voltages were perfectly balanced for the entire simulated period. A higher SAVUI indicated higher voltage unbalance. During normal operations, the three-phase voltages should be within 0.95-1.05 pu. The most unbalanced scenario would be when the three-phase voltages were at the two opposite extremes. When two phase voltages were 0.95 pu and the other phase voltage is 1.05 pu, the voltage unbalance were determined to be at maximum of 0.0678 pu. Therefore, the maximum value of SAVUI was:

$$max(SAVUI) = 0.0678 \tag{9}$$

### (4) System Control Device Operation Index (SCDOI)

The operations of voltage regulators and capacitors were separated in order to appropriately characterize each type of voltage control device.  $SCDOI_{VR}$  was defined as the Regulator Operation Index and  $SCDOI_{Cap}$  was defined as Capacitor Operation Index.  $TO_{VR,i}$  and  $TO_{Cap,j}$  were the total number of tap changes of the *i-th* voltage regulator and the total number

of switching operations of the *j-th* capacitor bank, respectively, for the entire studied time period. Both  $SCDOI_{VR}$  and  $SCDOI_{Cap}$  were defined based on a daily scale, as:

$$SCDOI_{VR} = \frac{\sum_{i=1}^{NR} TO_{VR,i}}{Tday \cdot NR} \quad SCDOI_{Cap} = \frac{\sum_{j=1}^{NC} TO_{Cap,j}}{Tday \cdot NC}$$
 (10)

Where, NR was total number of voltage regulators and NC was total number of capacitors. Tday is the total days studied.

If  $SCDOI_{VR}$  or  $SCDOI_{Cap}$  were zero, no tap changes or capacitor switching occurred during the simulated period. A non-zero value indicated that some control operations were needed to regulate voltage, potentially leading to the increased mechanical wear on the device. Electrical Power Transformer Engineering [13] provided typical LTC switching operation counts in various fields of application. The maximum number of operations for a power station transformer was 10,000 taps/year, and this value was used for determining the maximum value of  $SCDOI_{VR}$ . The maximum value of  $SCDOI_{Cap}$  was determined to be 4 operations/day, based on typical capacitor operation and two on-off operations per day.

### (5) System Reactive Power Demand Index (SRPDI)

The average of reactive power demands from the substation during the simulated period was used to define SRPDI, as:

$$SRPDI = \frac{1}{T} \sum_{t=1}^{T} Q_{sub}^{t} \tag{11}$$

Where,  $Q_{sub}^t$  was the substation reactive power demand at time t.

If SRPDI was zero, there was no reactive power demand from the substation for the simulated period, leading a substation power factor of 1.0. Increasing SRPDI would lead to lower power quality scores. IEEE Std C57.12.00-2015 [14] states that a transformer rating is based on a load power factor of 80% or higher. Therefore, 60% of the substation transformer MVA rating was used as the maximum allowable reactive power demand at the substation.

### (6) System Energy Loss Index (SELI)

System energy loss was used as another metric to evaluate power quality. Total energy loss during the simulated period was calculated and the total load demand was used as the dominator to normalize the energy loss. SELI was defined in (12) where Eloss was total energy loss during the entire simulation time;  $E_{load,i}$  was the energy demand of load-i throughout entire simulation time; and LN was the total number of loads observed.

$$SELI = \frac{Eloss}{\sum_{i=1}^{LN} E_{load,i}}$$
 (12)

The minimum value of SELI was zero, indicating an ideal system without loss. A larger SELI value would lead to a lower power quality score. An approximate range from 1.5% to 9% was observed by EPRI Green Circuit projects [8] so 9% is considered as the maximum value of SELI.

### B. Power Quality Score

PQS was determined based on the metric values of SAVMVI, SAVFI, SAVUI, SCDOI, SRDPI and SELI. The individual score for each power quality metric (denoted as

S(.)) is determined first using the linear correlation, illustrated in Fig. 3 and calculated using Eq. (13). The minimum value of each metric indicates the best power quality, which was given a score of 10. The maximum value of each metric indicates the worst power quality, which was given a score of 0.



Fig. 3. Linear correlation between power quality metric value and its individual score.

$$S(.) = 10 - \frac{10 \cdot (value(Metric_i) - \min(Metric_i))}{\max(Metric_i) - \min(Metric_i)}$$
(13)

Finally, PQS was a linear combination of six individual scores, as:

$$PQS = \alpha_{SAMVI} \cdot S(SAVMVI) + \alpha_{SAFVI} \cdot S(SAVFI) + \alpha_{SAUVI} \cdot S(SAVUI) + \alpha_{SCDOI} \cdot S(SCDOI) + \alpha_{SRPDI} \cdot S(SRPDI) + \alpha_{SELI} \cdot S(SELI)$$
(14)

Where,  $\alpha$  was the weight given to each index. The summation of all weights should be equal to 1.

In the following case study, a value of 1/6 was given to each weighting. It is noted that due to the limited industry standard information available, the limits that were used to normalize the six power quality metrics were based on different criteria, including theoretical, industry standard and practical limits. And this would unintentionally add additional weighting in the calculation of the overall PQS even though the average value of six metrics was used.

### IV. CASE STUDY

The utility distribution system studied in this paper had three feeders and a peak load of 37.1 MW. The nominal voltage was 21 kV and the substation bank size was 45 MVA. There were seven capacitors. The system was modeled using OpenDSS by the authors. All above voltage reduction and PQS methodologies were coded using Python. Multiple PV penetrations and smart inverter densities were studied to quantify the impact of distributed PV with smart inverters on voltage reduction energy savings and the PQS. Under a specified penetration level of PV systems and smart inverters, both PV locations and smart inverters were randomly allocated. PV and load data measurements in year 2015 were obtained and applied to each load and PV object. Finally the QSTS simulation was conducted for one year with 8,760 1-hour time steps.

### A. Without Voltage Reduction Optimization

Initially, CVR VO was not applied and the objective of utilizing smart inverters was to increase the PQS. The VVC used for all smart inverters had a center voltage of 1.0 pu, a vvcWidth of 0.01 pu and a deadband of 0.001 pu. The PQS was computed for each PV and smart inverter penetration scenario, and the results are given in Table I.

Without smart inverter penetrations, compared with the base case (0% PV) a higher PV penetration typically resulted in an increase in voltage fluctuation and voltage control device operations, i.e. decreasing scores for SAVFI and SCDOI;

while a higher PV penetration reduced the energy loss, i.e. increasing score for SELI; the impact of PV on SAVUI and SRPDI was negligible. SAVMVI always had a score of 10 because the voltage magnitude was always within 0.95-1.05 pu. When smart inverters were present, a higher smart inverter density helped increase the score of SAVFI. A significant improvement caused by smart inverters was observed for SRPDI. Table I shows that a higher PV penetration without smart inverter generally caused a lower PQS when compared with the base case, but the presence of smart inverters helped improve the PQS. The best PQS occurred when PV penetration was 50% and smart inverter density was 100%.

INDIVIDUAL SCORES AND PQS FOR VARIOUS SCENARIOS WITHOUT CVR VO

Scenario		Power Quality Individual Score						
PV	Smart Inv. (%)	M1	M2	M3	M4	M5	M6	PQS
0%	0	10	9.53	9.86	7.69	8.63	9.76	9.25
	0	10	9.51	9.87	7.69	8.68	9.73	9.25
10%	25	10	9.51	9.87	7.82	8.67	9.73	9.27
	50	10	9.52	9.87	7.96	8.66	9.73	9.29
	100	10	9.53	9.86	8.18	8.65	9.72	9.32
30%	0	10	9.46	9.85	7.68	8.75	9.62	9.23
	25	10	9.48	9.85	8.07	8.73	9.62	9.29
	50	10	9.50	9.84	8.44	8.71	9.61	9.35
	100	10	9.53	9.86	9.16	8.70	9.56	9.47
20%	0	10	9.42	9.87	7.68	8.81	9.44	9.20
	25	10	9.45	9.84	8.29	8.77	9.43	9.30
	50	10	9.48	9.87	9.15	8.75	9.38	9.44
	100	10	9.56	9.87	9.51	8.67	9.34	9.49
100%	0	10	9.34	9.87	7.69	8.79	9.07	9.12
	25	10	9.39	9.87	9.15	8.74	9.00	9.36
	50	10	9.47	9.88	9.51	8.66	8.97	9.42
	100	10	9.53	9.87	8.66	8.51	8.86	9.24

 $M1,\,M2,\,M3,\,M4,\,M5,\,M6$  are the individual scores for SAVMVI, SAVFI, SAVUI, SRPDI, SELI and SCDOI, respectively.

### B. With Voltage Reduction Optimization

When CVR VO was applied, the objective was to lower and flatten the voltage profile. Without PV or smart inverters, the implementation of the CVR VO which controlled the LTC and capacitors helped reduce energy consumption by 3.86%.

Fig. 4 shows the energy saving results for various scenarios after implementing CVR VO with PV systems and smart inverters. The VVC used in this study had a lower center voltage of 0.96 pu, a vvcWidth of 0.01 pu and deadband of 0.01 pu. With only one exception (5% PV + 50% smart inverter) a higher smart inverter density with the same PV penetration always led to larger energy savings. The largest energy savings was 4.3% when both PV penetration and smart inverter density were 100%.

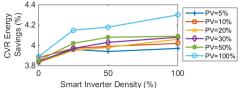


Fig. 4. Voltage reduction energy savings at different PV penetrations and smart inverter densities.

Fig. 5 shows the voltage profile at one time step obtained at various steps of the voltage reduction optimization. Compared without voltage reduction case, controlling substation LTC

and capacitors can reduce and flatten the voltage. After incorporating the smart inverter Volt-VAR control, the LTC was tapped down further; thus, increasing the voltage reduction energy savings.

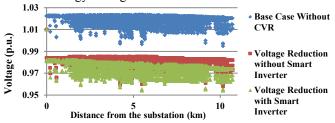


Fig. 5. Voltage profile at one time step obtained for three cases.

Table II shows the PQS results for various PV penetrations and smart inverter densities when voltage reduction optimization was implemented. Compared with Table I, a lower PQS was observed. This is because a much lower score of SCDOI resulted from the additional operations of the capacitors and LTC to lower and flatten the voltage profile to achieve higher energy savings.

If looking Table II only, higher smart inverter penetration generally led to lower PQS. This was mainly due to the reduced scores of SRPDI and SCDOI. Under a higher smart inverter penetration, the voltage reduction methodology would try to achieve more energy savings, which led to additional operations of capacitors and LTC.

TABLE II
INDIVIDUAL SCORES AND POS FOR VARIOUS SCENARIOS WITH CVR VO

Scenario		F	DOG					
PV	Smart Inv. (%)	M1	M2	M3	M4	M5	M6	PQS
0%	0	10	8.98	9.86	9.18	8.75	5.24	8.67
10%	0	10	8.92	9.86	9.14	8.78	4.89	8.60
	25	10	8.95	9.87	9.03	8.77	4.61	8.54
	50	10	8.99	9.87	9.00	8.76	4.74	8.56
	100	10	8.95	9.87	8.87	8.74	4.68	8.52
30%	0	10	8.91	9.85	9.19	8.87	4.93	8.62
	25	10	8.95	9.86	9.06	8.84	4.51	8.54
	50	10	8.95	9.88	8.93	8.81	4.41	8.50
	100	10	9.02	9.89	8.77	8.81	4.27	8.46
20%	0	10	8.88	9.87	9.20	8.93	4.61	8.58
	25	10	8.97	9.87	8.92	8.87	4.21	8.47
	50	10	9.02	9.90	8.77	8.87	3.94	8.42
	100	10	8.96	9.90	8.57	8.84	3.79	8.34
100%	0	10	8.94	9.87	9.10	8.90	4.35	8.53
	25	10	9.03	9.90	8.77	8.83	3.36	8.31
	50	10	8.99	9.90	8.56	8.80	3.18	8.24
	100	10	8.93	9.90	8.34	8.76	3.31	8.21

### V. CONCLUSIONS

This paper assessed the impact of distributed PV with autonomous smart inverter Volt-VAR control on voltage reduction energy savings and power quality. A methodology for CVR VO was developed to co-optimize the substation LTC, capacitor banks and smart inverters. A power quality scoring methodology was proposed to define the power quality using a single index. The key findings from the simulation study on one utility distribution system include:

(1) A voltage reduction scheme that flattens and lowers the distribution system voltage profile by controlling a substation LTC tap and switching capacitors can reduce overall energy consumption.

- (2) Voltage reduction energy savings increased with autonomous smart inverter Volt-VAR control. Smart inverters with a lower VVC band center allowed the tap position of the substation LTC to be lower, compared to cases without smart inverters. This resulted in a lower distribution system voltage profile and increased voltage reduction energy savings.
- (3) Since voltage reduction energy savings were prioritized over the PQS, the implementation of the proposed voltage reduction scheme lowered certain power quality scoring metrics, including SCDOI and SRPDI, leading to an overall lower PQS.
- (4) Overall without CVR VO, smart inverters had a positive impact on the PQS, and helped to reduce energy losses and voltage fluctuations.

It is worth noting that the impact of smart inverters could be inconsistent for various distribution systems due to distinct system characteristics. The methodologies proposed in this paper are repeatable and can be utilized to obtain the impact of smart inverters on the voltage reduction energy saving and power quality for any distribution system.

### REFERENCES

- [1] M. S. Chen, R. Shoults, J. Fitzer and H. Songster, "The effects of reduced voltages on the efficiency of electric loads," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 7, pp. 2158-2166, Jul. 1982.
- [2] R. H. Fletcher and A. Saeed, "Integrating engineering and economic analysis for conservation voltage reduction," in the proceeding of 2002 IEEE Power Engineering Society Summer Meeting, vol. 2, pp. 725-730.
- [3] A. Bokhari, *et al.* "Combined effect of CVR and DG penetration in the voltage profile of low-voltage secondary distribution networks," *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 286-293, Feb. 2016.
- [4] "Photovoltaic Impact Assessment of Smart Inverter Volt-VAR Control on Distribution System Conservation Voltage Reduction and Power Quality". NREL Technical Report, NREL/TP-5D00-67296, 2016.
- [5] S. R. Abate and T. E, "Smart inverter settings for improving distribution feeder performance". in 2015 IEEE Power & Energy Society General Meeting, pp. 1-5, Denver, CO, July 2015.
- [6] Analysis to Inform CA Grid Integration: Methods and Default Settings to Effectively Use Advanced Inverter Functions in the Distribution System. EPRI, Palo Alto, CA: 2015. 3002007139.
- [7] IEEE Std 1547a-2014, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems – Amendment 1, May 2014.
- [8] Green Circuits: Distribution Efficiency Case Studies. EPRI, Palo Alto, CA: 2011 1023518
- [9] Global Energy Partners, LLC, "Utility Distribution System Efficiency (DEI): Phase 1 – Final Market Progress Evaluation Report", Report #08-192, June 2008. [Online]. Available: <a href="http://neea.org/docs/reports/utility-distribution-system-efficiency-initiative-dei-phase-1-final-report-no-3.pdf">http://neea.org/docs/reports/utility-distribution-system-efficiency-initiative-dei-phase-1-final-report-no-3.pdf</a>.
- [10] American National Standard for Electric Power Systems and Equipment-Voltage Ratings (60 Hertz), NEMA ANSI C84.1-2011, 2011.
- [11] J. W. Smith, W. Sunderman, R. Dugan, and B. Seal, "Smart inverter Volt/VAr control functions for high penetration of PV on distribution systems," in *Proc. IEEE Power Systems Conference and Exposition (PSCE)*, Phoenix, AZ, March 2011, pp. 1–6.
- [12] IEEE Std 1453<sup>TM</sup>-2015, IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems, September, 2015.
- [13] J. H. Harlow, "Electric Power Transformer Engineering," CRC Press LLC, 2004, pp. 284.
- [14] IEEE Std C57.12.00<sup>TM</sup>-2010, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, Sep. 2010.